Journal of Cleaner Production 172 (2018) 3874–3889

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A proposal for integration of the ecosystem-water-food-land-energy (EWFLE) nexus concept into life cycle assessment: A synthesis matrix system for food security

Armağan Aloe Karabulut [a, b, *], Eleonora Crenna [b, c], Serenella Sala [b], Angel Udias [b]

[a] Ministry of Food Agriculture Livestocks, Soil Fertilizer and Water Resources Central Research Institute, Istanbul Yolu, 06171, Yenimahalle, Ankara, Turkey
[b] European Commission, Joint Research Centre, Directorate D- Sustainable Resources, Via E. Fermi 2749, 21027 Ispra, VA, Italy
[c] University of Milano-Bicocca, Department of Earth and Environmental Sciences, Piazza della Scienza 1, 20126 Milan, Italy

ARTICLE INFO

Article history:
Received 18 July 2016
Received in revised form
18 April 2017
Accepted 16 May 2017
Available online 17 May 2017

Keywords:
Ecosystem water food energy nexus
Life cycle assessment
Biofuel energy
Food security

ABSTRACT

Ensuring secure access to food and energy worldwide relies on win-win share of sectoral use of constrained natural resources such as land and water, taking also into account the crucial role of ecosystems and their services. The increase in global population and the related growing demand for food and other services are exerting unsustainable pressures on natural resources, compromising their use within the ecosystems' carrying capacity. Progressively, studies and initiatives have been developed with the aim of identifying win-win share strategies, which may compensate the sectoral demands of natural resources, addressing the need of a holistic and interdisciplinary nexus approach. In this study, thus emphasizing the importance of a holistic approach and highlighting the fundamental role of ecosystems, we propose a synthesis matrix system that describes the complex and closely bound relationship between natural resources use for food (specifically water, land), energy (defined as ecosystem service flows in our matrix system) and ecosystems, along the lines of the concept of ecosystem-water-food-land-energy nexus. The synthesis matrix system could be defined for different scales, both from the global to the local scale and has been designed to include impacts and nexus with climate change. The matrix aims at integrating quantitative and qualitative aspects, which are often neglected in traditional approaches of impact assessment. The complexity of the interactions between the different components of the nexus requires relying not only on quantitative evidences but also on expert judgment. A sensitivity check has been conducted to illustrate how to verify the convergence of expert-judgment from different experts. Moreover, being the matrix meant for supporting holistic assessment of supply chain, in the present study, the integration of the matrix within life cycle assessment (LCA) is proposed. However, in order to support the analysis of interconnections among impacts, further methodological development of the LCA methods is needed. An illustrative example related to the competition for water, land and food bioenergy production is depicted. The matrices show that there are predominantly negative impacts given by sectoral uses of resources on the provision of ecosystem services, an issue that requires most focus on resource efficiency and on the environmental and economic impacts of natural resources use while reducing the trade-offs between the sectoral demands.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Food, water, land and energy are fundamental and closely linked life-sustaining needs for human well-being as well for sustainable development (FAO, 2014; WWAP, 2014; Harvey and Pilgrim, 2011). Changes in the availability of water, land and energy supplies would strongly affect production of food, including the secure access thereof, with severe implications for human health (MEA, 2005; Gerbens-Leenes et al., 2009), particularly in developing countries that already experience serious resource scarcity conditions (Tilman et al., 2009).

The rapid increase in global population occurred over the last decades has exerted unmanageable pressures on natural resources,

* Corresponding author. Current address: TGAE-National Research Institute of Soil Fertilizer & Water Resources Istanbul Yolu, 06171, Yenimahalle, Ankara, Turkey.
E-mail address: armagankar@gmail.com (A.A. Karabulut).

http://dx.doi.org/10.1016/j.jclepro.2017.05.092
0959-6526/© 2017 Elsevier Ltd. All rights reserved.

compromising their sustainable use (Hoff, 2011; Tilman et al., 2009). In particular, population growth, as an independent driver of impacts, has played a significant part in not only increasing food (de Fraiture, 2007), water, land and energy demand worldwide (Gerbens-Leenes et al., 2009; Harvey and Pilgrim, 2011), but also correspondingly amplifying the adverse environmental and economic impacts of other enchained drivers such as urbanisation, land degradation, economic inequity, and climate change (Tilman et al., 2009). As a result of this continuum chain, the competition for natural resources between sectors such as agriculture and industry has increased, with unpredictable consequences for human well-being, economic growth and the environment (FAO, 2014; Ringler et al., 2013). It is all to the good that the increasing awareness of consumers and societies towards the selection of goods and services environmentally friendly produced, at least in the developing countries, is pushing the agricultural producers and industry to adopt more functional and sustainable production systems with the aim of improving their sectoral productivity, while protecting ecosystems and their functions. In fact, natural resources, particularly water and lands are shared by different sectors with different social and economic expectations. Political economy factors, particularly short term governmental economic plans aiming at leading to maximum economic benefit and economic growth, which may usually ignore minimizing environmental impacts, constrain the sustainable use of natural resources. Therefore, synergies with shared benefits among sectoral users of natural resources are still missing, also because of the management of water, land and energy generally takes place in isolation, without concrete consideration of the positive or negative impacts they have on other sectors.

Recently, to answer to the need of assessing the interplay between the different sectoral demands together to identify a win-win sectoral strategy of global resources management, a nexus concept among food, water, energy sectors (Hoff, 2011; Bazilian et al., 2011; Rasul, 2014; FAO, 2014) and ecosystems (ICIMOD, 2012; Bizikova et al., 2013) including land use (Ringler et al., 2013) has been proposed. Nexus concept describes the complex and closely bound relationship of human needs, natural resources and ecosystems on which human well-being rely to achieve socially, economically and environmentally sustainable goals (FAO, 2014).

Building on over 30 years of initiative for sustainable development, the recently released Sustainable Development Goals (2015) aim at safeguarding the long-term well-being of humankind by ensuring that agreed development (Weitz et al., 2014) is socially, economically and environmentally sustainable. In short, long-term sustainability requires integrated sectoral strategies by acknowledging that many natural resources such as water, land, fossil fuels and minerals are on the decrease because of their over-exploitation.

To better ensure the sustainable use of natural resources, resulting from the cooperation among sectors, in synergy with ecosystems and biodiversity, and to improve decisions in a Green Economy framework, this nexus approach requires the integration of life cycle thinking for each type of sectoral use, in order to avoid burden shifting and assess trade-offs among different environmental pressures and impacts. Life cycle thinking could be applied using different methodologies, namely life cycle assessment (LCA, ISO 14040, 2006; and ISO 14044, 2006), life cycle costing (LCC), social life cycle assessment (sLCA), and a further integrated methodology which is the life cycle sustainability assessment (LCSA) (Sala et al., 2013a, 2013b).

So far, very few studies have attempted an integration of life cycle thinking and assessment within the nexus framework. For example, Dale and Bilec (2014) developed a model for calculating life-cycle environmental impacts of regional energy and water supply scenarios (REWSS) using the water-energy nexus approach. The model was used to discuss future energy pathways in Pennsylvania, future electricity impacts in Brazil, and future water pathways in Arizona. Scott et al. (2011) proposed a study on LCC aiming at building policy awareness on the role of life cycle thinking to achieve the objectives of sustainable development, as well as sustainable service flows. However, there are not sufficient studies, which enlighten the uncertainties and gaps on holistic nexus perspective to refer the whole conceptual frame. Recently, Hang et al. (2016) develop a two-stage process systems engineering tools, an integrated design of the food-energy-water nexus that allows potential interactions between productions, combined with the concept of resource accounting using exergy for the design of local production systems for a designated eco-town in UK. The authors demonstrated the advantages of an integrated system making design centralising the supplies in local productions to meet local demands. In other work, Sanders and Masri (2016) proposed an approach integrating the remote sensing into integrated resource management communities so that technologies can be developed to assist in achieving sustainable development. The authors highlighted the opportunities and challenges that can guide technology development, researches and create new interdisciplinary research partnerships using the concept of food-energy-water nexus.

The Nexus concept has an intricate nature due to the complexity of its components (ecosystem, water, land, food and energy), that should be addressed together (Bazilian et al., 2011; Olsson, 2013) in order to provide solutions aiming at improving resource use efficiency. In this context, ecosystems represent the most important pillar of the nexus, since they incorporate all the features that support food, water, land and energy availability and production. However, this aspect increases the complexity of the nexus itself.

Therefore, we developed a nexus synthesis matrix system for food security, which places ecosystems and their services at the centre of the nexus and refers to the Common International Classification of Ecosystem Services (CICES) table (Haines-Young and Potschin, 2013). The objective of this system thinking is to identify the interrelations among the service flows related to the different sectors mentioned in the ecosystem-water-food-land-energy nexus. For instance, the effect of different sectoral energy, water and land demands onto the ecosystem services can be evaluated together by considering the life cycle impact assessment of each service flow correspondingly climate change and relevant European Union (EU) policies.

The standard LCA misses elements of interaction between impacts, which may largely affect the results of the assessment. The synthesis matrix coupled with standard LCA may improve substantially the analysis of agricultural systems. Therefore, the aim of this paper is to discuss the role of life cycle assessment of each service flow associated to different sectoral use of resources such as water and energy as pivotal complementary part of the proposed Ecosystem Water Food Land Energy (EWFLE) nexus. The issue of improving the impact assessment stage of LCA integrating qualitative aspects into quantitative ones has already emerged as a need, especially when bio-based/agricultural systems are involved (Sala et al., 2017; Notarnicola et al., 2017). Illustratively, the study shows how nexus and life cycle assessment can be integrated using a synthesis matrix system for food security to define better potential drivers of impacts and hotspots.

This paper is organized as follows: Section 2 presents the methodology adopted for investigating current nexus concepts and building the matrix, linking the EWFLE nexus and the life cycle assessment framework; Section 3 presents the resulting matrices and their integration in a life cycle assessment system thinking; Section 4, present the results, which are expert judgment based,

highlighting the utility of the synthesis matrix system in the challenges towards achieving sustainability goals, particularly within the agri-food sector.

2. Methods

A synthesis matrix which illustrates the relationship between interventions and impacts has been developed, focusing on Ecosystem Water Food Land Energy (EWFLE) nexus. The steps to build the matrix and to link the matrix to the life cycle assessment framework are:

- An evidence-based step, built upon a literature review to identify links between the element of the nexus (Section 2.1) towards the development of the synthesis matrix itself
- An expert-based step, which aims at identifying the type of link between impacts (positive/negative/neutral) assigning scores to the impacts (Section 2.2)
- The matrix integration within a life cycle assessment framework (Section 2.3)

2.1. Literature screening of possible nexus frameworks

There is a wide number of international initiatives to frame the water-food-land-energy nexus and define the close relationships between its components. The literature suggests that a holistic nexus-oriented approach is necessary to achieve sustainable growth, and to reduce unintended consequences and trade-offs of adopting narrowly sectoral approach (Hoff, 2011; World Economic Forum, 2011; ICIMOD, 2012; Bizikova et al., 2013). We reported in detail the most important initiatives about the nexus frameworks in the supplementary material (SM).

The shared focus of all the frameworks (in SM) is to promote joint actions with multi-purposed policy strategies to reduce trade-offs, enhance synergies across sectors and provide sustainable growth. Apart from the frameworks, there are studies: (i) highlighting the importance of and arguing deeply the nexus approach (Beck and Walker, 2013; FAO, 2014; Kibaroglu and Gürsoy, 2015; Wong and Pecora, 2015; Wong, 2015); (ii) recommending solutions with holistic approaches by simplifying the complex nexus cyclic system using different combination of nexus components (Allouche et al., 2015; Bhaduri et al., 2015; FAO, 2014); (iii) and analyzing regionally or globally the status to facilitate the implementation of nexus approach (Lawford et al., 2013; Holtermann and Nandalal, 2015; Daher and Mohtar, 2015; Mohtar and Daher, 2016; Mohtar, 2016). For the sake of example to practical consequences and interactions of joint actions and policy strategies, Gain et al. (2015) analyzed nexus institutional issues in the context of Bangladesh and suggested policy integration for policy implementation. Halbe et al. (2015) present a methodological framework to analyze sustainability innovations in the Water- Energy- Food (WEF) nexus and strategies for governing transition processes in Cyprus. Hensengerth (2015) analyzes the limited influence a water-centred organization has on hydropower development, and addresses the issue of authority and hegemony in the field of international development and hydropower policy, using a case study of the Xayaburi Dam in the Lower Mekong Basin.

With the framework we proposed in this study, we believe that the involvement in life cycle assessment of each sectoral action included into the holistic nexus approach and defined with a synthesis matrix system would provide different beneficial dimensions, including those related to governance. For instance, this could facilitate the involvement of the stakeholders in the solutions and decision making process towards multi-participation.

2.1.1. Matrix development for water for food, energy for food, ecosystem for food

As proposed by ICIMOD (2012) and Bizikova et al. (2013), we emphasized the importance of ecosystems and their services in providing water, energy and food supply, posing them in the centre of our nexus framework (Fig. 1).

Ecosystems and their services are central in our scheme as they are crucial and vital elements for human well-being. This is also recognized through their incorporation into environmental policies and initiatives at international level (MEA, 2005; TEEB, 2010; Scarlett and Boyd, 2011; EC, 2011).

In this matrix system, we took into consideration only provisioning ecosystem services; the remaining services (supporting, regulating and cultural) were not included in the paper, since this research work represents the first attempt to explain how this newly developed matrix basically works. In addition to this, in our matrix, land has been included under the concept of ecosystem with the thought that the term of land embraces soil ecosystems and different land uses and land covers e.g., grasslands, heathlands, forests, agricultural, urban ecosystems.

According to the framework we proposed in Fig. 1, we prepared a synthesis matrix system consisting of three matrices for the EWFLE nexus in form of a double entry table in order to identify the relationships between sectoral uses of resources and the role of provisioning ecosystem services, accounted to as reported in CICES classification (Haines-Young and Potschin, 2013).

Given the complexity of the interactions between the different components of the nexus, it requires relying not only on quantitative evidences but also on expert judgment. Examples exists of integration of historical evidence, expert judgment and statistical approaches to improve impact assessment (e.g. Muxika et al., 2007).

According to our experiences based on integrated watershed modeling to support mapping ecosystem services (Karabulut et al., 2015), we listed the possible nexus service flows, meaning flows of water, energy and food used for a specific sectoral use, like water for drinking, water for agriculture etc. We classified these service flows according to the possible types and sub-types of sectoral uses, referring to either final or intermediate services which directly or indirectly affect human well-being. For instance, within the types of "water for food" service flows, we accounted water for drinking, water for any food (crops and meat) productions, water for all household uses for food etc. as final services, while we considered available soil water as intermediate service supporting the food production as green water.

Then we built our double entry table, in which we localized sectoral uses of resources (sectoral service flows), in the rows and provisioning ecosystem services of CICES in the columns. The cell resulting from the meeting between a row and a column defines the relationship between a specific sectoral use of resources and the selected ecosystem service. In this way, we obtained three matrices to set up synthesis matrix system for food security, one for each resource category considered, i.e. "water for food", "energy for food" and "ecosystem for food". These matrices are detailed in section 3 (Tables 1–3).

The main purpose of the proposed synthesis matrix system is to build a frame that gatheres around the ecosystems and their services to support the nexus approach. Therefore, we used CICES table to demonstrate also the synergies and the antagonisms (i.e. conflicts) between the nexus service flows, explained in the paragraph below.

2.2. Scoring systems for assessing the directionality of the relationships within nexus

In this study, we assumed that an illustrative study area is

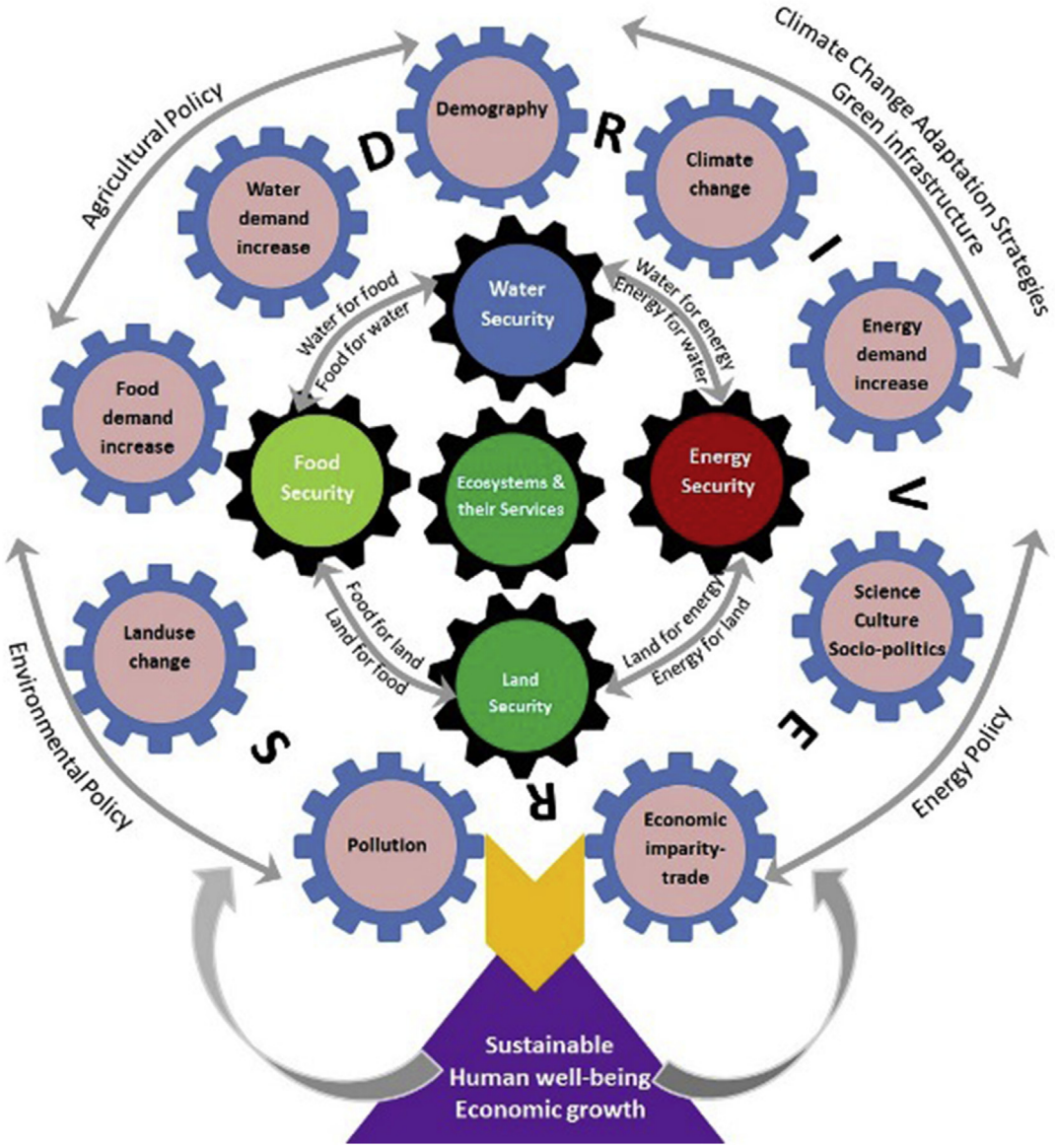

Fig. 1. Framework for the ecosystem-water-land-food-energy security nexus. Political, socio-economic and environmental drivers are posing a risk to the provision of ecosystem services, which are central life-sustaining elements for human well-being and resource supply as well as green economic growth. The close relationships between ecosystem services, secure access and supply of natural resources and external drivers are explained through the holistic and integrated approach proposed in the EWFLE nexus framework.

located in a region undergoing possible water and energy stress. Based on qualitative expert judgment, we determined the possible impacts of several service flows underpinning food security (e.g. the use of water for drinking or irrigation, energy for agriculture) on the ecosystem provisioning services. Within the matrix system, we defined the interrelations between the service flows (or sectoral actions) (i.e. rows in the matrices) and ecosystem provisioning services (i.e. columns in the matrices) considering possible impacts (alternatives). Differently from the CICES classification system, we included abiotic outputs from natural systems (abiotic provisioning such as minerals, fuels, clays, marbles etc.) together with biotic ecosystem services, since they might also act as a driver affecting each other positively or negatively. For instance, agricultural machineries, such as fertilizer spreaders, sowing machines, harvesting machines etc., are required to produce crops, which generally consume fossil fuel (an abiotic output of ecosystems) as non-renewable abiotic energy source. While fossil fuel is supporting the services for food, food production is creating an antagonistic effect on fossil fuel resource by consuming it with use of agricultural machineries and afterwards use for transporting the foods, which could be determined better using LCA.

Integrated holistic impact assessments require an integrated modelling approach (Boumans et al., 2002; Tallis and Polasky, 2009; Villa, 2009; Müller et al., 2010) enabling to involve in and assess all related sectoral dynamics in the model. Physical, geographical and geomorphological characteristics of the interested area, current and suggested policies related to relevant sectors to be implemented, socio-cultural and economic structures are major input data for such models. Due to the difficulties of obtaining such data and complexity of the interconnected impacts, we classified the possible impacts of each service flow based on expert judgment. Other examples in literature are using expert judgment to integrate quantitative and qualitative aspects, especially when the latest are very complex and interconnected (see e.g. Burkhard et al. (2012) for assessing ecosystem services) and the actions and ecosystem services of the synthesis matrix system

Table 1
Synthesis Matrix for water-food-energy nexus versus ecosystem provisioning services: "water for food" case.

SYNTHESIS MATRIX for ECOSYSTEM-WATER-FOOD-ENERGY NEXUS (Modified after CICES_V3 and V4.3)	ECOSYSTEMS' PROVISIONING SERVICES							
	Nutrition		Materials			Energy		
WATER FOOD ENERGY SERVICE FLOWS	BioM	PoW	BiotM	AbioM	NPoW	RBioE	NRBioE	RAbioE
WATER (GW&SW) FOR FOOD (withdrawn, consumed, returned)								
Water for drinking	★	★	★	★	★	★	★	★
Water for irrigation	★	★	★	★	★	★	★	★
Available soil water (green water) for crop production	★	★	★	★	★	★	★	★
Water for livestock fattening								
Water for slaughter house								
Water for managing farms								
Water for agri-industrial productions (agricultural machineries, fertilizer, pesticides, herbicides, etc.)								
Water for apiculture								
Water for fisheries								
Water for aquaculture								
Water for forest farming/agroforestry								
Water for horticulture								
Water for transferring foods (inland navigations)								
Water for manufacturing, refining, packing the foods								
Water for washing vegetables, fruits etc., by end-users (eg., at home, restaurants and hotels)								
Water for prepare food at home, restaurants, hotels, refectories etc.								
Water for cleaning food remains by end-users								
Water for waste treatment								

BioM: Biomass, PoW: Potable water, BiotM: Biotic materials, AbioM: Abiotic materials, NPoW: Non-potable water, RBioE: Renewable biomass based energy sources (plant, animal), NRBioE: Non-renewable fossil energy, RAbioE: Renewable abiotic energy sources (hydropower, wind, etc...)

Direct positive (Dp) /Supporting (S)	Direct negative (Dn) /Conflicting (C)	Dp or S/ Dn or C	Dn or C/ Dp or S	Neutral /Not clear

could be changed depending upon interested area. The approach we used can be transformed into such an integrated model to assess interrelated impacts at local, national and global scale elaborately and somehow quantitatively. As stated by Burkhard et al. (2012), by linking real information from e.g. remote sensing, land survey and GIS with data from monitoring, statistics, modeling or interviews, ecosystem service supply and demand can be assessed and transferred to different spatial and temporal scales. In our study, we classified the directionality of the impacts of each service flow of the nexus on provisioning ecosystem services with in a specific case-study as follows:

- direct positive and supporting (secondary positive) effects (i.e. synergic), colored in green color;
- direct negative and conflicting (secondary negative) effects (i.e. antagonistic), colored in red;

Table 2
Synthesis Matrix for water-food-energy nexus versus ecosystem provisioning services: "energy for food" case.

SYNTHESIS MATRIX for ECOSYSTEM-WATER-FOOD-ENERGY NEXUS (Modified after CICES_V3 and V4.3)	ECOSYSTEMS' PROVISIONING SERVICES							
	Nutrition		Materials			Energy		
	BioM	PoW	BiotM	AbioM	NPoW	RBioE	NRBioE	RAbioE
WATER FOOD ENERGY SERVICE FLOWS								
ENERGY FOR FOOD								
Energy for agricultural management practices (Striping, bulking, seeding, planting, fertilizing, sowing, applying&controlling weeds, pests or disease, harvesting etc.)								
Energy for management of farms or state hatchery								
Energy for delivering water to agricultural areas								
Energy for operating irrigation system								
Energy for livestock fattening								
Energy for poultry husbandry								
Energy for apiculture								
Energy for fisheries								
Energy for aquaculture								
Energy for horticulture								
Energy for disposing of waste from an agricultural activity								
Energy for transporting food (crop, livestock, etc.) to process (hauling) (transporting in-country, intercountry)								
Energy for processing food (manufacturing, refining, grading, packaging)								
Energy for transporting food to the markets (transporting in-country, intercountry)								
Energy for per capita to have food at home								
Energy for preparing food at home or restaurant, hotels, refectories etc.								
Energy for collecting organic wastes								
Energy for other food procedures (energy for pruning etc.)								
Energy for agri-industrial productions (fertilizer, pesticides, herbicides industrial productions etc.)								
Solar energy for net primary productivity (NPP) in terrestrial and marine ecosystems (The rate at which new biomass accrues in an ecosystem)(Higher in humid and warmer climate, less in dry and hot climate)	★	★	★	★	★	★	★	★

BioM: Biomass, PoW: Potable water, BiotM: Biotic materials, AbioM: Abiotic materials, NPoW: Non-potable water, RBioE: Renewable biomass based energy sources (plant, animal), NRBioE: Non-renewable fossil energy, RAbioE: Renewable abiotic energy sources (hydropower, wind, etc...)

Direct positive (Dp) /Supporting (S)	Direct negative (Dn) /Conflicting (C)	Dp or S/ Dn or C	Dn or C/ Dp or S	Neutral /Not clear

Table 3
Synthesis Matrix for water-food-energy nexus versus ecosystem provisioning services: "ecosystems for food" case.

SYNTHESIS MATRIX for ECOSYSTEM-WATER-FOOD-ENERGY NEXUS (Modified after CICES_V3 and V4.3)	ECOSYSTEMS' PROVISIONING SERVICES							
	Nutrition		Materials			Energy		
WATER FOOD ENERGY SERVICE FLOWS	BioM	PoW	BiotM	AbioM	NPoW	RBioE	NRBioE	RAbioE
ECOSYSTEM FOR FOOD								
Marine ecosystems (fish, crustacean, molluscs, echinoderms etc.)	★	★	★	★	★	★	★	★
Lentic (lakes, reservoirs, ponds) ecosystems (fish, some vertebrates, duck,)	★	★	★	★	★	★	★	★
Lotic ecosystems (fish, some vertebrates,)	★	★	★	★	★	★	★	★
Wetlands (Fish, duck, etc.)	★	★	★	★	★	★	★	★
Forest ecosystems (all berries, honey, mushroom, seed, nut, root, tuber, gums, sap, wild animals (pork) etc.)	★	★	★	★	★	★	★	★
Agro-ecosystems (all cultivated crops)	★	★	★	★	★	★	★	★
Grasslands and heathlands (rabbits, wild pork, etc.)	★	★	★	★	★	★	★	★

BioM: Biomass, PoW: Potable water, BiotM: Biotic materials, AbioM: Abiotic materials, NPoW: Non-potable water, RBioE: Renewable biomass based energy sources (plant, animal), NRBioE: Non-renewable fossil energy, RAbioE: Renewable abiotic energy sources (hydropower, wind, etc...)

Direct positive (Dp) /Supporting (S)	Direct negative (Dn) /Conflicting (C)	Dp or S/ Dn or C	Dn or C/ Dp or S	Neutral /Not clear

- not clear, colored in grey, used in situations in which we were not sure of the direction of the impact or if there is no provision of those services in relevant study area. The neutral environmental and economic impacts are also considered in this class. Within the matrix, indirect effects were addressed with the supporting and conflicting classes.

Indeed, while some service flows have explicit negative or positive impacts, some others can have either positive or negative impacts on ecosystems or their capacities of providing services, according to the thresholds they may have. In some cases, over time there can be a transition from positive to negative effects when the above-mentioned threshold (in a real case study) is overcome. For the sake of example, very severe water scarcity in the Atacama region, which resulted from being located in a hyper-arid climate, in Chile, creates a serious conflict between copper mining industries which necessitates considerable amount of water in production process and ingenuous public water demand (drinking water, and household water use) and agricultural water demand (Budds, 2010). The conflict is, actually, not only on the water quantity but also on pollution contributions to water quality in the region. In such a region where priority should be assigned to water for drinking and households use, when water is used primarily for the advantage of mining activities, this creates negative impacts on drinking water, and irrigation water provisioning services that resulted in a decrease in biomass production. There are indicators or indexes to determine thresholds quantitatively. For example, water scarcity indexes, e.g. Falkenmark water scarcity index (FLK) (Falkenmark, 1989) or Water exploitation index (WEI+) (EEA, 2017), are usually used to define the thresholds for water scarcity. In another example, the allowable nitrate concentrations in water resources are determined for Europe with nitrate (EU, 1991). However, interrelations between the actions and ecosystem services, and their thresholds representing degree of the impacts (direct positive/supporting or direct negative/conflicting), can be defined by integrated models and scenarios with real data. In another example, according to our matrix, energy for wastewater treatment may either affect crop production positively, since water returning to the environment is cleaner and has less negative effect in terms of water quality; or negatively, since a huge amount of energy is used for water treatment in case of water scarcity and competitions among water user sectors arise. Similarly, drained water returning to the riverine or lentic ecosystems or ground waters from agro-ecosystems could be a gain in terms of quantity, while this agricultural returning water might have antagonistic affect in terms of quality if there is over fertilizer or pesticide use in those agricultural areas. However, we cannot claim that this returning water could be either positive or negative driver for the abiotic material (except for table salt resources) or non-renewable energy resources of provisioning services. Therefore, being unable to define the direction of the effect, we identify this relationship as "not clear" in our subjective assessment.

The distinction between services and benefits is still under discussion due to different terminology used for different scientific disciplines. As an example, while some consider the recreation as a cultural ecosystem service, some others claims that this is the benefit serviced by ecosystem's physical characteristics (Haines-Young and Potschin, 2013). Therefore, without distinguishing between services and benefits, we adopted either final ecosystem services or benefits to represent the service flows of nexus.

To disclose the role of climate change into the nexus concept, we signed tables with stars, which represent the potential of

ecosystem services to be directly or indirectly affected by climate change. It is to be noted that this is an impact analysis exercise, expert judgment-based, which could be subject to consultation with other experts when it has to be used to run specific case studies at local scale. The matrix we present has an illustrative purpose on a fictive example. Optionally - and beyond experts - local stakeholders may be involved in the evaluation of the elements of the matrix, improving transdisciplinarity of the impact assessment and relevance for local conditions. Moreover, this also ensure that the synthesis matrix could be adjusted related to local conditions, namely involving specific experts in the definition of the matrix and even local stakeholders.

2.3. Conceptual framework for linking the developed matrixes and LCA

Life cycle thinking and assessment have been initially conceived as concept and method for integrated impact assessment. Few examples exist on studies mentioning the use of LCA for exploring nexus, but they have a relatively limited scope (e.g. Feng et al. (2014) focusing on the water energy nexus in the Chinese context; Qiu et al. (2014) assessing effect on agriculture). Methodologically, the assessments are conducted using input-output approaches, hence with a sector-based scale (e.g. Mekonnen et al., 2016; Wang and Chen, 2016).

Hence, exploring the potential of integrating the nexus concept and matrix within the LCA method is discussed. In fact, each service flow in the matrix may be related to certain stages of a life cycle of a product and/or element of the cause-effect chain adopted in life cycle impact assessment. Moreover, the provision of a product may generate impacts that may, following a causal chain, negatively affect other service flows. In the example of crop production for food versus bioenergy, the water, withdrawn from either groundwater or surface water, is delivered to the agricultural areas to irrigate the crops. The type of irrigation system and the type of crop also makes difference on the amount of water used, economic conditions of the producer, and on the impacts to the environment. However, the water deprivation derived from the production may affect ecosystems services that are needed for a future production. For this reason, each service flows in the synthesis matrix system should be evaluated in terms of its link with a life cycle stage, its effects on environment, economy and society. Therefore, in this paper we explore the potential integration of water-food–land-energy nexus with life cycle assessment at two levels: i) LCA results informing the assessment of the impacts in the synthesis matrix; ii) the results of the synthesis matrix, to be used as a qualitative complement of LCA applied to e.g. agricultural systems, supporting the identification of potential hotspots of impacts neglected by traditional impact assessment models.

3. Results: EFWLE nexus synthesis matrix system for food security

The matrices of “water for food”, “energy for food” and “ecosystem for food” that we obtained and some practical related examples are presented in the following sections.

Each cell of the matrices reports the qualitative assessment of the possible impact, according to the majority of the experts. Since assessing such matrices takes long time, we used limited number of expert judgment to make inferences about population of interest. Estimation on sensitivity involves the calculation of confidence intervals (95% Confidence intervals- 95% CI) for a proportion of experts' judging each cell of the matrices. Even though the results may vary from sample-to-sample, we are “confident” because the margin-of-error would be satisfied for 95% of all samples (with $z^* = 2$). The expected lower rate of experts (the lower level of confidence interval) judging the alternatives with 95% confidence interval (Gardner and Altman, 1989) in the matrices is illustrated in the Supplementary tables (Table SM1, SM2 and SM3). Logically, the value 100 indicates that all experts have voted the same alternative. The degree of the agreement, as well (Cohen, 1960), among the experts on the possible impacts in the matrices was illustrated with Cohen's kappa indicator in the SM tables. We preferred using Cohen's kappa indicator because it is a statistical measure on inter-rater-agreement used commonly for categorical item (Warrens, 2010) which we have in our matrices case and, in general, it is a more robust measure than the percentage of agreement because the kappa takes account of the agreement occurring by chance.

The general level of concordance and agreement of the experts is very high for the most of the statements of the survey (see 100% values in Table SM1, SM2, and SM3). However, the experts do not agree with the possible impacts of water for food actions on the NRBioE (Non Renewable fossil energy) (Table SM1), as well as the energy for food actions on BioM (Biomass) (Table SM2), of the assessment.

3.1. Water for food

At the global level, the greatest amount of freshwater withdrawals, approximately 80% of blue water, plus a large fraction of green water, is used for agricultural purpose in order to support food production (Hoff, 2011; MEA, 2005). This feature is projected to increase by 10% by 2050 (FAO, 2014). Moreover, “virtual agricultural water”, consumed during food production processes and embedded in national or international food trade or import is increasing argument in the challenges about global water scarcity (Allan, 2003). On the other side, rain-fed croplands require less water supply due to the use of only available soil water content (green water) than the irrigated crops. In addition, about 10% of irrigation water in developing countries comes from reused wastewater (MEA, 2005). The sharing of water among different agricultural activities in the water-poor regions creates an antagonism because these activities compete against each other to receive sufficient amount of water supply.

We may interpret the following matrix observing how, in water scarcity condition, a sectoral use of water (e.g. water used for drinking purpose) affects an ecosystem service (e.g. biomass production, which is an example for crop production). The relationship may be addressed as direct and negative because the amount of potable water, which is taken from the environment and processed for drinking, becomes unavailable for producing crops. As already mentioned, it is crucial to put the accent on the water scarcity condition, because if water was abundant in a region and there was no water scarcity issue, it may not be possible to recognize the positive or negative effects in short term.

Given that in the water scarce hypothetical study area the sectoral water demands and sectoral service flows are as in Table 1, conflicts in water scarce area (which food security might have priority among other, e.g. energy security) may explicitly become clearer than those of water abundant areas (Carpenter et al., 2005; UN-UNITAR, 2016). Therefore, water use for interventions such as crop cultivation, horticulture, livestock flattening, apiculture to ensure food security, as given in Table 1, may have positively adjuvant impacts on biomass provisioning services. However, if there are, as well, mining activities supporting abiotic resource provisioning or fossil fuel productions in this water-scarce area, given the water use priority assigned to the food security, water allocated to food security may effect negatively other sectoral provision services e.g. potable water (PoW), biotic materials (BiotM), renewable biomass based energy sources (plant, animal)

(RBioE), renewable abiotic energy sources (hydropower, wind, etc.) (RAbioE) (Table 1). As previously mentioned, provision services of abiotic materials (AbioM), non-renewable fossil energy (NRBioE) (grey colored in Table 1), and may be negatively (in red color) affected by securing food production if there is mining activities or fossil fuel production in the competition of water supply. Moreover, if there are crops dedicated to biofuel energy production and crops for food provision, the use of water might be in competition in water scarcity conditions. On the other hand, available soil water content, depending on the precipitation amount and timing, increases not only the rain-fed (green water) crop production, but also biomass of natural vegetation cover other natural food production such as food derived from forest farming. It should not be forgotten that those conflicts may not be explicit in water abundant areas.

Addressing the impacts of forest farming, we may consider that forest farming is an agro-forestry system applied as an alternative to conventional agricultural farming, which provides marginal land becoming productive for food security as well as wildlife preserved, pollution decreased and the beauty of landscapes enhanced (Douglas and Hart, 1976) and flood risks controlled (Calder, 2002). According to the matrix (Table 1), we may say that water for forest farming and related agri-industrial production supports biomass growth; contrary, the use of water for those same farming and manufacturing processes can create a conflict with the water required for drinking, irrigation and other energy use.

Moreover, water required for aquaculture or fisheries in the dam lakes may support sufficient amount of water for renewable abiotic (water) energy, while increasing water demand for aquaculture can turn into a negative conflicting effect. In fact, in water scarcity conditions, the increasing amount of water reserved for aquaculture or fisheries related needs can create a conflict with, for example, the potable or irrigation water needs.

Because water resources recharge depends on meteorological factors -such as precipitation, evapotranspiration, etc.-, any change in the climate conditions may directly affect freshwater resources supply and its provisioning services (Hamlet and Lettenmaier, 1999; Vörösmarty et al., 2000; Christensen et al., 2004; Jentsch and Beierkuhnlein, 2008; Piao et al., 2010). The IPCC technical paper (Bates et al., 2008) on climate change and water stated that, globally, the negative impacts of future climate change on freshwater systems are expected to be drastic. By the 2050s, the area of land subject to increasing water stress due to climate change is projected to be more than double that with decreasing water stress. The increasing global population means more demand for agriculture, greater use of water for irrigation and more water pollution. Therefore, changes in water quantity and quality due to climate change are expected to affect food availability, stability, access and utilisation. This may lead to decreased food security and increased vulnerability of poor rural farmers, especially in the arid and semi-arid regions (Bates et al., 2008). Under these assumptions, we signed with stars the nexus actions that are likely to be directly and mostly affected by the climate change. However, this does not mean that the non-signed actions are not affected by climate change. Using this approach, we assumed that most of non-signed actions are affected by climate change indirectly. The table shows clearly that food security is highly affected by climate change (Table 1) as indicated by Bates et al. (2008).

3.2. Energy for food

Food production and its supply chain consume significant quantity of energy, particularly in developed countries (Olsson, 2013) where mechanization and other modernization measures are adopted. In fact, at the global level, the food sector accounts for nearly 30% of the total energy consumption, and more than 70% of that energy is used beyond the farm gate (FAO, 2014). Within the agriculture and food production context, energy is used in different ways. For instance, it is employed directly to heat and cool buildings, operate agricultural equipment such as tractors, pump water for irrigation, transport products to the market, etc. Moreover, energy use is interconnected between various sectors, from agriculture to industry. In fact, as an example, modern farms that produce meat and dairy products raising numerous animals in industrial livestock need access to quantities of feed such as grain fodder. Fodder production, in turn, requires huge amounts of pesticides and synthetic fertilizers, which are produced by pharmaceutical industry using notable energy input deriving from the use of fossil fuels as row material. Besides, fodder production requires fossil or bio fuels for crop cultivation. Consequently, any type of energy source is crucial for global food security. The status of energy is inadequate and primarily used to ensure food security (the actions to produce food in the synthesis matrix), may have negative impact on NRBioE and AbioM provisioning (Table 2).

Benchmarking the components of energy for food versus provisioning services provided by ecosystems may vary depending on the energy sources used (Table 2). For instance, production of fossil fuels consumes a considerable amount of water during its life cycle chain. The production of shale gas is more water intensive than conventional natural gas due to water required for hydraulic fracturing (Clark et al., 2013). The amount of water used in fossil fuel production can result in conflicts between the NRBioE and NPoW and/or PoW in areas with high water stress/low water availability or in times of drought (Clark et al., 2013). Therefore, if energy is procured from fossil fuel for agricultural management practices (i.e. striping, bulking, seeding, planting, fertilizing, sowing, applying & controlling weeds, pests or disease, harvesting etc.), it will have supporting effects on biomass production, while having conflicting effect on potable and non-potable water provisioning because of water consumption in the fossil fuel production processes. In addition, energy required for irrigation in food production may compete against energy required for bio-fuel production or for other sectors.

According to the matrix in Table 2, collecting, transporting and disposing organic waste (included in the table as “energy for disposing of waste from agricultural activity”) are energy-consuming activities that directly affect fossil fuels availability, if the fossil fuel is used. However, there are systems that can produce their bio-energy using the waste. In most of cases, the organic waste is accumulated as biomass source to produce biogas, which is also used in public transportations. For instance, since 1994, buses in Lille (North of France) have been using biogas fuel as well as in Sweden, Linköpping and Uppsala (EBA, 2015). In this way, biogas plays an important role in reducing the dependence on fossil fuels as renewable environmentally friendly energy production.

As another example from the matrix, fertilizers are used to provide nutrients to support soil productivity and to increase crop production, while pesticides and herbicides are used to protect the crops and keep yield in the maximum level. However, at the same time these activities have the potential to damage the environmental sustainability as a contaminant if they are overused. Furthermore, herbicides and pesticides may also damage some living organisms in the soil. In addition, ammonia and urea can be produced from different hydrocarbon feedstocks such as natural gas, coal, and oil and one of the end uses for urea are ammonia is fertilizers. Therefore, the use of natural gas as an input in the production of fertilizer (Ammonia Outlook, 2002; Urea Outlook, 2002; Ramírez and Worrell, 2006), and petroleum and natural gas as input for pesticides production (Ware, 1983; Lee, 1991) can create a conflict with the supply of abiotic material and fossil fuels, since

such agrochemicals consume great amount of abiotic material during their processing phase. On one hand, their use supports the food biomass production as supporting effect (Kuniuki, 2001; Cooper and Dobson, 2007), while overuse may increase the environmental pollution as a conflicting negative effect (Kovach et al., 1992; Miller, 2004).

The solar energy required by the net primary productivity in terrestrial and marine ecosystems should also be considered in the "energy for food" loop in order to better define the conditions and environmental life cycle impact of drivers. For instance, greenhouse gases with their contribution to climate change are the main drivers affecting the functions and intensity of solar energy. Proper amount of solar energy can support biomass provisioning, in a way that higher in humid and warmer climate, less in dry and hot climate (Ruimy et al., 1999), to ecosystems. However, anomalies related to the increase in solar energy that reach the Earth's surface could create conflicts by sometimes causing drought, contrary less solar energy create colder climate proportionally reducing the biomass provisioning. As an example, an increasing trend in solar energy and temperature against the decreasing or stable rainfall trend may negatively affect water and biomass provisioning because of draughtiness (Schmidhuber and Tubiello, 2007; Chaouche et al., 2010).

In Table 2, focusing on actions with stars, it is possible to observe that climate change is directly responsible for changes in the provision of energy for net primary productivity in both land and marine ecosystems, e.g. agricultural crop yields (Rosenzweig and Parry, 1994), forest and marine biomass productions (Beier et al., 2004). Therefore, under our assumptions, the other cells within the matrix are considered as indirectly affected by climate change. For the sake of example, climate change may alter the season cycle affecting directly the provision of solar energy for biomass production; this can be considered an example of direct action of climate change. An example of indirect impact would be the same in a case where biomass is used as a source of energy. That is, climate change can directly affect the production of biomass of biofuel plants; while indirectly affect the transportation of food or other actions that use biofuel as a source of energy for transporting the goods.

3.3. Ecosystem for food

The availability of adequate resources (e.g. water, fuels) and energy for food production depends on ecosystems' quality and their ability to provide services. Particularly, agro-ecosystems, marine ecosystems and forests are the main source of nutrient provisioning services in most regions. Forest ecosystems provide wide-range of food such as different varieties of berries, mushrooms, nuts, roots, tubers and wild animals, which are very important predominantly in the most rural economy. In most cases, forests also support water-provisioning and regulation services. Correspondingly, agro-ecosystems provide humankind with crops and livestock. However, beside their importance in nutrient provisioning services, agro-ecosystems compete with other water demanding sectors to receive sufficient amount of water for irrigation. Furthermore, due to over-fertilization, agro-ecosystems still may threat waters and ecosystems like lotic, lentic and marine aquatic ecosystems, which have great importance on food security as well.

According to the matrix in Table 3, ecosystems play a pivotal role in supporting the provision of services within the context of a sustainable system. They predominantly have direct and positive effects on the availability of energy and matter for food production. An important example is represented by pollination. Pollination is an essential ecosystem service for primary producers in both wild and managed terrestrial ecosystems (Klein et al., 2007; Kremen et al., 2007; Zulian et al., 2013). In fact, it represents a crucial ecosystem service primarily supporting the provisioning of the food services such as honey, which is a direct food production by bees, and supporting pollination function to produce crops, fruits etc. in the agri-food sector. Intensified agricultural practices, particularly the massive use of pesticides, are likely to affect pollination mediated by insects, posing a risk to global food security. Agro-chemicals can quickly degrade pollination services acting through the loss of species (Potts et al., 2010; Sandrock et al., 2014), and those remaining species would be unable to compensate for the difference (Kremen, 2005). Since pollinators are particularly vulnerable to environmental stress (Kevan, 1999), pollination requires healthy environmental conditions in order to provide us with functioning ecosystems and services. Hence, pollination is a vital service not only for biomass provisioning (e.g. crops), but also for regulating the provision of final goods and services, such as water provisioning for its healthy ecological requirements.

Grounded the fact that the fossil fuels formed from decayed plants and animals (or ecosystem biomass services hundred millions of years ago) over hundred millions of years (Hubbere, 1949), we should acknowledge that the ecosystems will proceed its role on generation of fossil fuels for the future time. Therefore, in the synthesis matrix we considered that ecosystems will continue its positive impacts on NRBioE generations and services.

Ecosystems and their biodiversity are highly dependent on the climate factors (Beier et al., 2004; Jeppesen et al., 2009). Therefore, all the service flows within the matrix are considered as directly affected by the climate change in the table of ecosystem for food (Table 3). In a similar vein, EPA (2010) The climate change warms up the oceans and effects the temperature at the surface and at depths which can be resulted as change in the habitat and food supplies for many kinds of marine life—from plankton to polar bears.

3.4. Integration between LCA and the EWFLE nexus synthesis matrix system

Life cycle assessment method is devoted to the environmental integrated impact assessment of supply chains (ISO 14040 and ISO 14044, 2006). Since the nexus concept is linked to several stages of a product life cycle (e.g. agricultural phase, production and transformation, distribution, consumption and end of life stages), the assessment of the integration should follow two steps: one related to the identification of the elements of the matrix in the system boundary of an illustrative LCA study, a second one in the identification of the impacts that may lead to modification in the input to the system (e.g. affecting water availability, soil quality etc).

This means that the life cycle inventory and the life cycle impact assessment may be improved for accounting for the elements of the nexus matrix. This is of upmost importance. In literature, the issue of improving the impact assessment stage of LCA integrating qualitative aspects into quantitative ones has already emerged as a need, especially when bio-based/agricultural systems are involved (Sala et al., 2017; Notarnicola et al., 2017). Standard LCA applied to agricultural system misses several potential drivers of impacts and hotspots whose identification could be helped by the application of the synthesis matrix.

To illustrate these steps, we present an illustrative example for the possible life cycle assessment of biodiesel crop production within a system in competition with food crop production (Fig. 2). In details, the system boundaries of the object of the study may be such to support the identification of the potential occurrence of interrelations between input/output of the system. This requires to explicitly mentioning which elements are crossing the boundary between ecosphere and technosphere. This means that cubic

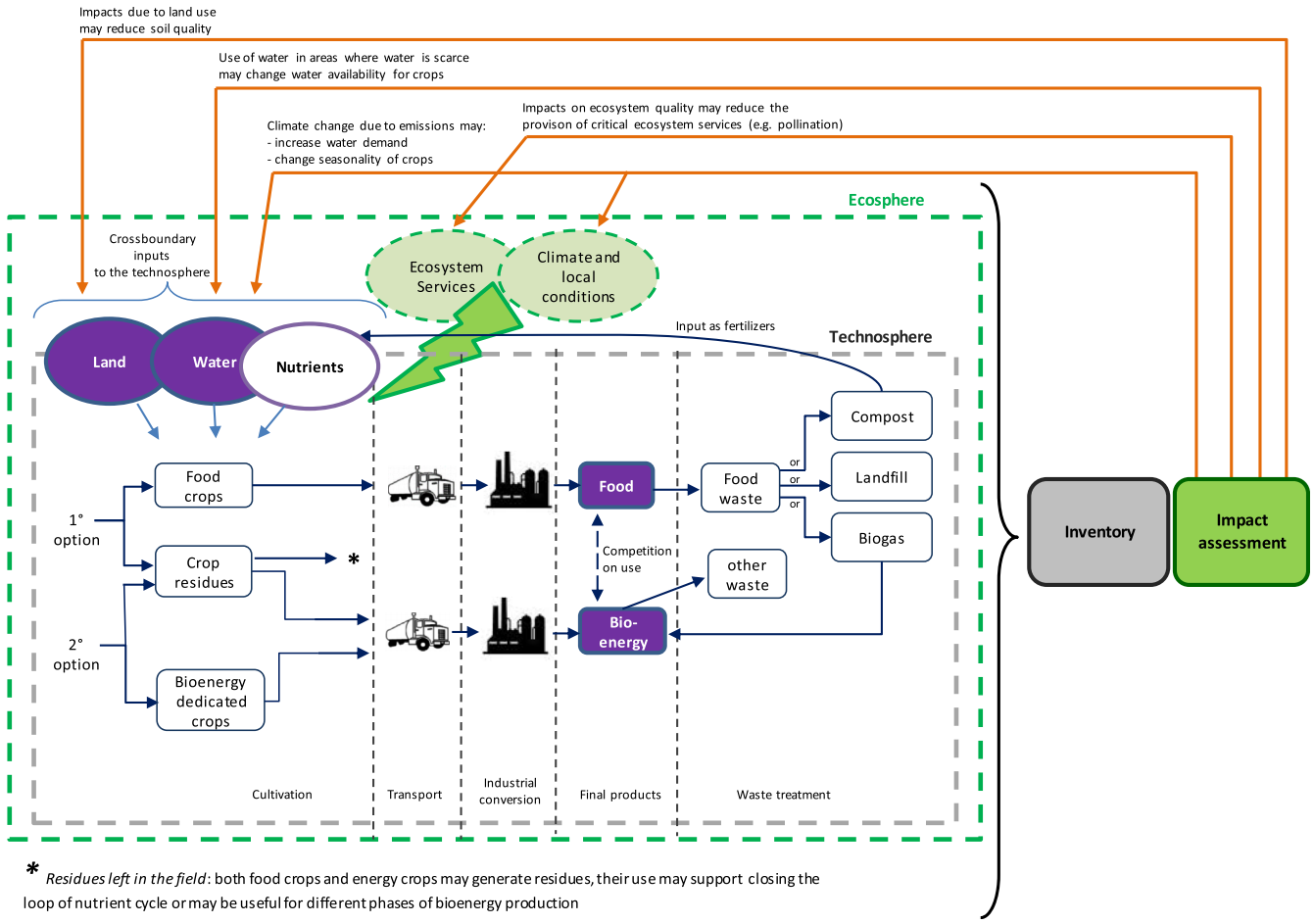

Fig. 2. Conceptual framework for the integration of life cycle assessment and nexus matrix, illustrating an example for food and bioenergy crops. The impacts related to different uses may trigger negative consequences such as damage to human well-being, resources' supply and ecosystem functioning and those may feedback back to critical input to the production system of either bioenergy or food.

meters of water or square meters of land are identified as input, however, they are in between ecosphere and technosphere, due to their close relationship and interdependency with ecosystems (soil of a certain quality is the result of bio-geological cycles, water availability is related to climatic conditions but also to the soil texture etc.). Beyond input explicitly mentioned in inventories (such as water, land, nutrients) other elements such as ecosystem services of different nature (e.g. pollination) are essential for an agricultural supply chain but are not mentioned. Even if their quantification is difficult, their existence and role should be acknowledged.

Based on those inputs, a production chain of crops may be depicted, leading to production of food or bioenergy. This system boundary is usually adopted as reference for building the life cycle inventory (emission and resource used in each stage) and for, in a second stage, calculating the impact (with a set of impact assessment models, see Fig. 3).

However, in order to apply the matrixes and the nexus concept, this is not enough. Moving from linear to circular systems, in which feedback back to the ecosphere are taken into account, especially for those elements explicitly accounted for (land/water) or not accounted for (ecosystem services) which are both crucial for the delivery of the final output in the tecnosphere. The nexus approach aims at understanding the link between the impacts due to the production of a product on the inputs necessary for a future production.

Biofuel related impacts have mainly been evaluated in relation to their positive contribution to reduce greenhouse gas emissions and to meet green energy demand, while the potential increase in water use, which may generate competition with other sectors, has received minor attention (Brentrup et al., 2004; Kim and Dale, 2005; Emmenegger et al., 2011). In fact, neglecting to consider overall environmental impacts related to a process or product may cause biased misleading incentives, such as, in the presented case supporting biofuel crop production without taking into consideration the water scarcity in the watersheds. However, nevertheless, very limited work (Emmenegger et al., 2011 (Argentina); Pfister et al., 2009; Chiu et al., 2009 (USA); Dominguez-Faus et al., 2009) has been performed to assess the impacts deriving from freshwater use in LCA studies on biofuel crop production. This is due to the lack of regional inventory data and more focus on climate change adaptation only by reducing green gas emissions.

Basically, in future, nexus of three typologies may be assessed in a LCA framework:

1. Those occurring between elements of the system boundaries and that may lead to competitions of uses
2. Those related to impacts that may occur due to the production of a certain good and that may imply reduction of ecosystem quality and services, as well as of critical inputs (e.g. water, land), implying a negative effect on future production

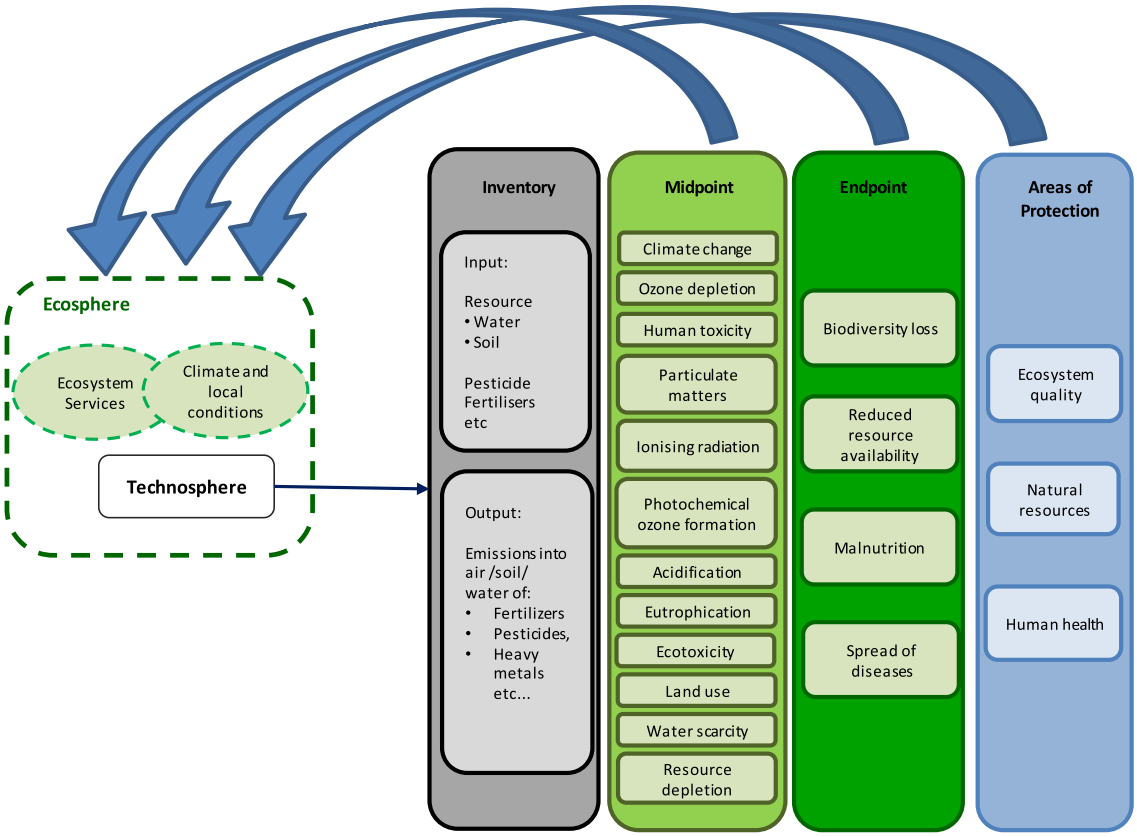

Fig. 3. Life cycle assessment: from the inventory of emissions and resources, impacts are assessed considering a huge variety of impacts. However, so far, no feedback to the original inputs has been envisaged to be measured or reported. The impact categories referred to those recommended by the ILCD list of models for impact assessment (EC-JRC, 2011).

3. Those positive feedback that could be related to identify possible sources of resources to be used in a synergetic manner (e.g. recovery of nutrients that may support the substitution of a chemical fertilizer, use of compost on soil, etc.)

Some of these concepts are already embedded in the so-called consequential LCA (e.g. elements that may lead to competition of uses), others not (such as the interplay between impacts) and require in future a dedicated analysis for being further explored and systematized. Indeed, the consequential approach intends to describe how physical flows can change as a consequence of an increase or decrease in demand for the product system under study, including unit processes inside and outside of the product's immediate system boundaries (Earsel and Halog, 2011). The traditional consequential assessment covers the life cycle inventory, whereas, the proposed approach add on top impact assessment aspects and could be considered a sort of consequential impact assessment. The two level of consequential analysis (inventory and impact assessment) may then complement each others.

The life cycle assessment for each nexus service flows mentioned above in each table (1, 2, and 3) could be developed and included into the nexus synthesis matrix system. It is crucial to assess these impacts either spatially explicit or at least regionally: for this aim, spatially resolved life cycle impact assessment models could be used. However, since each region has its own different sectoral uses or ecosystem service flows, it is more convenient to set up site-specific local nexus synthesis matrix system with its own service flows and their life cycle assessments for each region.

Moreover, the synthesis matrix itself could be used for a qualitative hotspot analysis to complement the quantitative results of LCA, highlighting potential impacts not covered by current impact assessment methods.

3.5. Supporting economic growth adopting the EWFLE security nexus matrix

The EWFLE Nexus matrix, especially if integrated with supply chain related considerations by LCA, may be used to analyze the current environmental and economic impacts of all service flows in a target area. This may be done adopting a site-specific synthesis matrix system, which could results from consulting several experts as well as local stakeholders. In this regard, it is inevitable to include explicitly economic, institutional and policy aspects of the EWFLE nexus as mentioned by Markantonis et al. (2015) in order to promote economic growth potentials in the target region. Thereby, in this discussion paper we propose three-dimensional (3D) structure for the EWFLE Nexus to support economic growth (Fig. 4).

The socio-economic growth based on holistic nexus approach can be achieved by optimization using the feedback of three dimensions (policy, institutions and economy). For examples, policies devoted to energy or water security, may create negative affect on food security or vice versa (Fig. 4). Therefore, as mentioned above describing Tables 1–3, when it is aimed at enhancing synergies between sectoral actions and provisioning ecosystem services, policy-institution-economy dimensions should be taken into account, as well, to achieve optimal cross-cutting policies and to ensure economic benefits from nexus components. Fig. 4 illustrates the point (Ex,Iy, Pz) where an optimization of cross-cutting objectives is reached, covering economic, institutional and political optimum. The green point is a function of the policy-economic-institution interconnection that represents the optimal combination of environmental impacts and economic benefits shared by all dimensions.

Sustainability related impacts on environmental and socio-

economic dimensions should be evaluated in a life cycle thinking framework, namely towards the maximization of the societal benefit while minimizing negative environmental and socio-economic impacts. Some preliminarily attempt of coupling optimization models and LCA have been performed (e.g. You et al., 2012). However, the challenge of including the feedback into the input system accounting for nexus is not yet developed.

4. Discussion

The synthesis matrix system we developed for food security is an example for the system thinking nexus approach by highlighting the importance of the ecosystem functioning and integrating with LCA. Since the nexus concept is linked to several stages of a product life cycle, the life cycle inventory and the life cycle impact assessment may be improved for accounting for the elements of the matrix. The synthesis matrix should be considered as a methodological guidance to assess interaction between environmental pressure and compartments on a context-specific basis. Hence, the general matrix depicted by our work is referring to a general tendency in nexus between environmental aspects. This means, that the matrix, if applied in a context where, e.g. water stress conditions are extreme, the interplay between the elements of the matrix may change significantly.

The synthesis matrix system explains the interrelationships using an imaginary case-assessment between the service flows (actions in the nexus) and the ecosystem provisioning services. They are considered as speculative, that means that the relationships are evaluated in qualitative terms, without having been ranked on a quantitative assessment basis. We believe that assessing the impacts with real quantitative data using life cycle for each actions would give more concrete and reliable results. However, the matrices system showed that there are predominantly negative impacts on the provision of ecosystem services given by sectoral uses of resources especially in case of land and water scarce regions. Therefore, because provisioning more water and land could not be possible in such regions, the future researches may need more focus on efficiency and on the environmental and economic impacts of natural resources' use, while reducing the trade-offs between the sectoral demands.

Comparing Tables 1 and 2 with Table 3, it is obviously seen that ecosystems has almost completely direct or supporting positive impacts on food security, thus enhancing food production. While the increasing human demand for natural resources poses a risk to resource supply itself and thus on the provision of ecosystem services, functioning ecosystem themselves are able to enhance food production and ensure access to food globally. This positive impact of ecosystems explicitly shows that to be sustainable it is inevitable to include also the ecosystems and their services security into each policy and implementation related to the food, water and energy as also mentioned in Bizikova et al. (2013).

Even though obtaining the holistic view of every impact involved in the activities of those sectors that use resources is very complex, and difficult mostly due to the lack of reliable data, it is necessary to evaluate actual environmental and economic impacts of any sectoral service flow in the nexus in order to avoid any conflict between sectoral uses in the future projections. Thus, assessments by setting simplified local synthesis matrix system may solve the complexity, while easing to observe the entire system. To simplify and better determine quantitatively the interrelationships between the service flows within the nexus and the provisioning ecosystem services, multi-disciplined biophysical and economical models can be integrated or interactively used, e.g., LEAP (SEI, 2015a), WEAP (SEI, 2015b), InVEST (Tallis et al., 2011), SWAT (Arnold et al., 1998), EPIC&APEX (Texas A&M AgriLife Research, 2015) IMAGE (Stehfest et al., 2014). Commonly SWAT and WEAP models are used for watershed managements, EPIC&APEXS is used for land management impacts and crop production, LEAP is used for

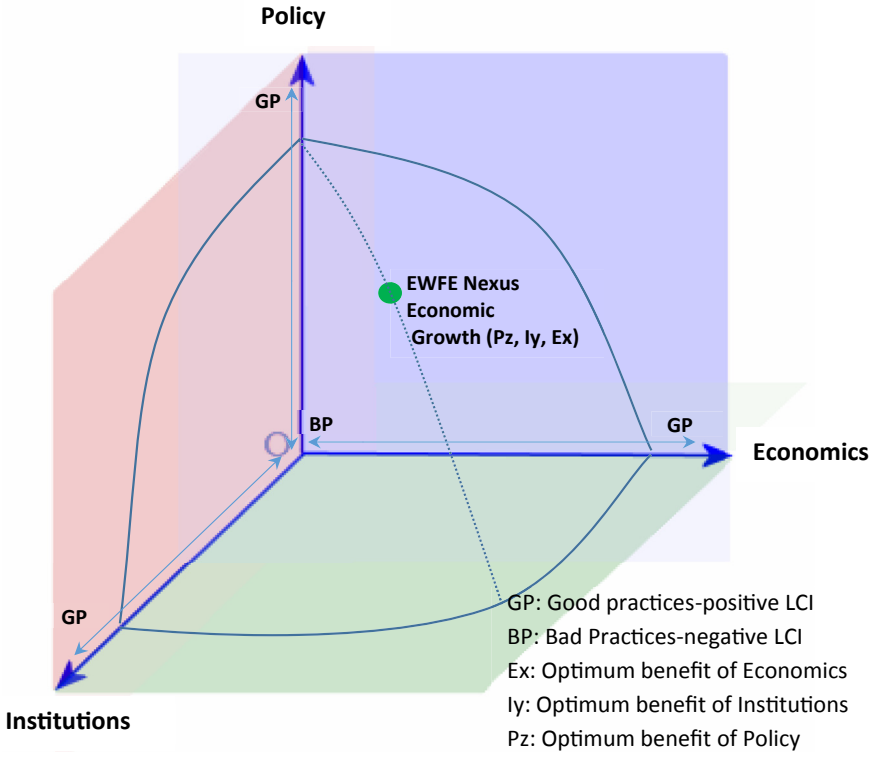

Fig. 4. Three dimensional EWFLE Nexus Definition Model for promoting sustainable economic growth.

sustainable energy analysis, IMAGE is used to assess global environment, and InVEST is used to model ecosystems and their services.

Furthermore, policy, economics and institutions, the most important primary management mechanisms of the nexus, could be linked to the synthesis matrix system to identify the cross-cutting policies or good/bad implementations by each institution with different economic perspectives regarding each component of the nexus (i.e. ecosystem, water, food, energy).

Increasing demand and unbalanced sectoral share not only induce drastic depletion of natural resources but also make explicit the need of sectoral interdisciplinary management strategies. Therefore, the method proposed in this study could be a holistic interdisciplinary way to acquire well-matched cross-cutting policies, inter-institutional relations between the nexus components. As mentioned before, taking advantage of enhancing synergies between sectoral actions and provisioning ecosystem services (described by nexus synthesis matrix system) using LCA assessment and integrated models, an interdisciplinary holistic policy making system can, as well, be constituted, taking into account of policy-institution-economy triangle dimensions related to the EWFLE nexus to ensure sustainable green economic growth.

5. Conclusion

Water, food, land and energy are essential for human well-being and economic growth. Agriculture has the dominant use of natural resources primarily for food production and, in terms of land, this activity involves approximately 50% of the land area in the EU-27 and 2.4% of the European agricultural area is devoted to organic production (EU: 5.7%) (Eurostat, 2015). Within this context, ecosystem, water, food, land and energy are inextricable interrelated, in that concept called Ecosystem-Water-Food-Land-Energy Nexus. The Nexus concept represents a challenge towards the achieving of sustainability goals, especially within the agri-food sector. Although their use is shared by different sectors such as agriculture and industry, water and energy have so far been considered in isolation. This lack of cooperation between sectors has led to significant competition between the different use of energy and water for food or for other purposes. This is reflected in contradictory strategies and policies, which do not effectively permit to reach either economic or environmental sustainability, posing a risk to global food security. Water, food, land and energy need to be addressed simultaneously, in order to develop strategies to enhance positive synergies between sectoral uses, share benefits and meet the increasing demand, still protecting the ecosystems and their functioning.

Therefore, given the importance of the environmentally friendly agriculture sector for ensuring secure access to food, we felt the need to exercise the interrelationships among EWFLE nexus sectors and integrated assessment methods, such as life cycle assessment. With the synthesis matrix system, we aim to march forward, towards the identification and simplification of the trade-offs synergies or conflicts between sectoral service flows as well as their life cycle impacts for food security. However, the LCA framework requires adaptations to improve the comprehensiveness of the impact evaluation, in light of capitalizing the theoretical underpinning of the nexus and translating it into a quantitative assessment of the impacts.

The novelty of the matrix we proposed goes for this purpose, since it stands in the proposal of a qualitative assessment to evaluate the effective relationships between natural resource uses and ecosystems, which underpin resources' supply. The matrix can be adapted from elaborative local scale to global scale to investigate the trade-offs, that is synergies or antagonisms, with research-based quantitative thresholds. We hope that it will inspire further analysis and lead to in-depth studies on how to make food security as functional and sustainable as possible, improving synergies among sectoral demands and uses.

For future work, we highly recommend multi-disciplined studies to improve this system thinking synthesis approach to clarify the gaps or uncertainties while working globally or locally on the matrix. Therefore, any recommendation on terminology or on categorization of the service flows and on identifying the synergy is welcome to improve the matrix for different purposes and locations.

Acknowledgements

The authors acknowledged the experts from the European Commission, Joint Research Centre and IPBES network for their participation and great contributions to this study. The authors acknowledged, as well, Yioannis Trichakis for his great contribution to the matrix assessment of the study.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.05.092.

References

Allan, J.A., 2003. Virtual water-the water, food, and trade nexus. Useful concept or misleading metaphor? Water Int. 28 (1), 106–113.
Allouche, J., Middleton, C., Gyawali, D., 2015. Technical veil, hidden politics: interrogating the power linkages behind the nexus. Water Altern. 8 (1).
Ammonia Outlook, 2002. Issue 2002-1. Fertecon Ltd, Kent, UK.
Arnold, J.R., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment. Part I: model development. J. Am. Water Resour. Assoc. 34 (1), 73–89.
Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P. (Eds.), 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva, p. 210.
Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R.S.J., Yumkella, K.K., 2011. Considering the energy, water and food nexus: towards an integrated modelling approach. Energy Policy 39 (12), 7896–7906. http://dx.doi.org/10.1016/j.enpol.2011.09.039.
Beck, M.B., Walker, R.V., 2013. On water security, sustainability, and the water-food-energy-climate nexus. Front. Environ. Sci. Eng. 7 (5), 626–639.
Beier, C., Emmett, B., Gundersen, P., Tietema, A., Penuelas, J., Estiarte, M., Gordon, C., Gorissen, A., Llorens, L., Roda, F., Williams, D., 2004. Novel approaches to study climate change effects on terrestrial ecosystems in the field: drought and passive nighttime warming. Ecosystems 7 (6), 583–597.
Bhaduri, A., Ringler, C., Dombrowski, I., Mohtar, R., Scheumann, W., 2015. Sustainability in the water–energy–food nexus. Water Int. 40 (5–6), 723–732.
Bizikova, L., Roy, D., Swanson, D.A., Venema, H.D., McCandless, M., 2013. The Water–Energy–Food Security Nexus: towards a Practical Planning and Decision Support Framework for Landscape Investment and Risk Management. IISD paper. IISD Publications Centre, p. 29.
Boumans, R., Costanza, R., Farley, J., Wilson, M.A., Portela, R., Rotmans, J., Villa, F., Grasso, M., 2002. Modeling the dynamics of the integrated earth system and the value of global ecosystem services using the GUMBO model. Ecol. Econ. 41, 529–560.
Brentrup, F., Küsters, J., Kuhlmann, H., Lammel, J., 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment methodology: I. Theoretical concept of a LCA method tailored to crop production. Eur. J. Agron. 20 (3), 247–264.
Budds, J., 2010. Water Rights, Mining and Indigenous Groups in Chile's Atacama. In: Out of the Mainstream. Water Rights, Politics and Identity, pp. 197–211.
Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012. Mapping ecosystem service supply, demand and budgets. Ecol. Indic. 21, 17–29.
Calder, I.R., 2002. Forests and hydrological services: reconciling public and science perceptions. Land Use Water Resour. Res. 2 (2), 1–12.
Carpenter, S.R., Pingali, P.L., Bennett, E.M., Zurek, M.B., 2005. Ecosystems and Human Well-being: Scenarios, vol. 2.
Chaouche, K., Neppel, L., Dieulin, C., Pujol, N., Ladouche, B., Martin, E., Caballero, Y., 2010. Analyses of precipitation, temperature and evapotranspiration in a French Mediterranean region in the context of climate change. Comptes Rendus Geosci. 342 (3), 234–243.
Chiu, Y.W., Walseth, B., Suh, S., 2009. Water embodied in bioethanol in the United States. Environ. Sci. Technol. 43 (8), 2688–2692.

Christensen, N.S., Wood, A.W., Voisin, N., Lettenmaier, D.P., Palmer, R.N., 2004. The effects of climate change on the hydrology and water resources of the Colorado River basin. Clim. Chang. 62 (1–3), 337–363.
Clark, C.E., Horner, R.M., Harto, C.B., 2013. Life cycle water consumption for shale gas and conventional natural gas. Environ. Sci. Technol. 47 (20), 11829–11836.
Cohen, J., 1960. A coefficient of agreement for nominal scales. Educ. Psychol. Meas. 20, 37–46.
Cooper, J., Dobson, H., 2007. The benefits of pesticides to mankind and the environment. Crop Prot. 26 (9), 1337–1348.
Daher, B.T., Mohtar, R.H., 2015. Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water Int. http://dx.doi.org/10.1080/02508060.2015.1074148.
Dale, A.T., Bilec, M.M., 2014. The regional energy & water supply scenarios (REWSS) model, Part I: framework, procedure, and validation. Sustain. Energy Technol. Assess. 7, 227–236.
de Fraiture, C., 2007. Integrated water and food analysis at the global and basin level. An application of WATERSIM. Water Resour. Manag. 21 (1), 185–198.
Dominguez-Faus, R., Powers, S.E., Burken, J.G., Alvarez, P.J., 2009. The water footprint of biofuels: a drink or drive issue? Environ. Sci. Technol. 43 (9), 3005–3010.
Douglas, J.S., Hart, R. A. de J., 1976. Forest farming. In: Towards a Solution to the Problems of World Hunger a Conservation, p. 215. ISBN: 0-87857-228-7.
Earsel, J.M., Halog, A., 2011. Consequential life cycle assessment: a review. Int. J. Life Cycle Assess. 16 (5), 445–453.
EBA (European Biogas Association), 2015. Position Papers & Press Releases. Available at: http://european-biogas.eu/ (Accessed November 2015).
EC (European Commission), 2011. Our Life Insurance, Our Natural Capital: an EU Biodiversity Strategy to 2020. Communication from the Commission COM/2011/0244 final.
EC- JRC, 2011. Recommendations Based on Existing Environmental Impact Assessment Models and Factors for Life Cycle Assessment in European Context. Publications Office of the European Union, Luxembourg. EUR24571EN. ISBN 978-92-79-17451-3. Available at: http://eplca.jrc.ec.europa.eu/ (Accessed November 2015).
EEA (European Environment Agency), 2017. Water Exploitation Index. Available at: https://www.eea.europa.eu/data-and-maps/figures/water-exploitation-index-plus-wei (Accessed January 2017).
Emmenegger, M.F., Pfister, S., Koehler, A., de Giovanetti, L., Arena, A.P., Zah, R., 2011. Taking into account water use impacts in the LCA of biofuels: an Argentinean case study. Int. J. Life Cycle Assess. 16 (9), 869–877.
EPA, 2010. Climate Change and Ecosystems. Available at: https://www3.epa.gov/climatechange/downloads/Climate_Change_Ecosystems.pdf (Accessed April 2016).
Eurostat, 2015. Eurostat Statistics Explained - Agriculture Statistics at Regional Level. Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Agriculture_statistics_at_regional_level (Accessed December 2015).
European Union, 1991. Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Official J. 375 (31), 12.
Falkenmark, M., 1989. The massive water scarcity threatening Africa-why isn't it being addressed. Ambio 18 (2), 112–118.
FAO, 2014. The Water-Energy-Food Nexus A New Approach in Support of Food Security and Sustainable Agriculture. Achieved at: http://www.fao.org/nr/water/docs/FAO_nexus_concept.pdf (Accessed 20/11/2015).
Feng, K., Hubacek, K., Siu, Y.L., Li, X., 2014. The energy and water nexus in Chinese electricity production: a hybrid life cycle analysis. Renew. Sustain. Energy Rev. 39, 342–355.
Gain, A.K., Giupponi, C., Benson, D., 2015. The water–energy–food (WEF) security nexus: the policy perspective of Bangladesh. Water Int. 40 (5/6), 895–910. http://dx.doi.org/10.1080/02508060.2015.1087616 [Taylor & Francis Online].
Gardner, M.J., Altman, D.G., 1989. Statistics with Confidence: Confidence Intervals and Statistical Guidelines.
Gerbens-Leenes, P.W., Hoekstra, A.Y., Van der Meer, T., 2009. The water footprint of energy from biomass: a quantitative assessment and consequences of an increasing share of bio-energy in energy supply. Ecol. Econ. 68 (4), 1052–1060.
Haines-Young, R., Potschin, M., 2013. Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August-december 2012. EEA Framework Contract No EEA/IEA/09/003.
Halbe, J., Pahl-Wostl, C., Lange, M.A., Velonis, C., 2015. Governance of transitions towards sustainable development – the water–energy–food nexus in Cyprus. Water Int. 40 (5/6), 877–894. http://dx.doi.org/10.1080/02508060.2015.1070328 [Taylor & Francis Online].
Hamlet, A.F., Lettenmaier, D.P., 1999. Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin, 1.
Hang, M.Y.L.P., Martinez-Hernandez, E., Leach, M., Yang, A., 2016. Designing integrated local production systems: a study on the food-energy-water nexus. J. Clean. Prod. 135, 1065–1084.
Harvey, M., Pilgrim, S., 2011. The new competition for land: food, energy, and climate change. Food Policy 36, S40–S51.
Hensengerth, O., 2015. Where is the power? Transnational networks, authority and the dispute over the Xayaburi Dam on the Lower Mekong Mainstream. Water Int. 40 (5/6), 911–928. http://dx.doi.org/10.1080/02508060.2015.1088334 [Taylor & Francis Online].
Hoff, H., 2011. Understanding the Nexus. Background Paper for the Bonn2011 Conference: the Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm.
Holtermann, T., Nandalal, K.D.W., 2015. The water–energy–food nexus and climate change adaptation. Change Adapt. Socio Ecol. Syst. 2 (1), 122–124.
Hubbere, M.K., 1949. Energy from Fossil Fuels.
International Centre for Integrated Mountain Development (ICIMOD), 2012. Contribution of Himalayan Ecosystems to Water, Energy, and Food Security in South Asia: a Nexus Approach. International Centre for Integrated Mountain Development, Kathmandu, Nepal.
ISO 14040, 2006. Environmental Management—life Cycle Assessment— Principles and Framework. Geneva, Switzerland.
ISO 14044, 2006. Environmental Management—life Cycle Assessment— Requirements and Guidelines. Geneva, Switzerland.
Jentsch, A., Beierkuhnlein, C., 2008. Research frontiers in climate change: effects of extreme meteorological events on ecosystems. Comptes Rendus Geosci. 340 (9), 621–628.
Jeppesen, E., Kronvang, B., Meerhoff, M., Søndergaard, M., Hansen, K.M., Andersen, H.E., Lauridsen, T.L., Liboriussen, L., Beklioglu, M., Özen, A., Olesen, J.E., 2009. Climate change effects on runoff, catchment phosphorus loading and lake ecological state, and potential adaptations. J. Environ. Qual. 38 (5), 1930–1941.
Karabulut, A., Egoh, B.N., Lanzanova, D., Grizzetti, B., Bidoglio, G., Pagliero, L., Bouraoui, F., Aloe, A., Reynaud, A., Maes, J., Vandecasteele, I., Mubareka, S., 2015. Mapping water provisioning services to support the ecosystem-water-food-energy nexus in the Danube river basin. Ecosyst. Serv. doi:10.1016/j.ecoser.2015.08.002.Open access.
Kevan, Peter G., 1999. Pollinators as bioindicators of the state of the environment: species, activity and diversity. Agric. Ecosyst. Environ. 74 (1), 373–393.
Kibaroglu, A., Gürsoy, S.I., 2015. Water–energy–food nexus in a transboundary context: the Euphrates–Tigris river basin as a case study. Water Int. 40 (5/6), 824–838. http://dx.doi.org/10.1080/02508060.2015.1078577 [Taylor & Francis Online].
Kim, S., Dale, B.E., 2005. Life cycle assessment of various cropping systems utilized for producing biofuels: bioethanol and biodiesel. Biomass Bioenergy 29 (6), 426–439.
Klein, A.M., Vaissiere, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proc. R. Soc. B Biol. Sci. 274, 303–313.
Kovach, J., Petzoldt, C., Degni, J., Tette, J.A., 1992. Method to Measure the Environmental Impact of Pesticides (New York's Food and Life Sciences Bulletin No. 139, Cornell Univ., Ithaca).
Kremen, C., 2005. Managing ecosystem services: what do we need to know about their ecology? Ecol. Lett. 8, 468–479.
Kremen, C., Williams, N.M., Aizen, M.A., Gemmill-Herren, B., LeBuhn, G., Minckley, R., Packer, L., Potts, S.G., Roulston, T., Steffan-Dewenter, I., Vazquez, D.P., Winfree, R., Adams, L., Crone, E.E., Greenleaf, S.S., Keitt, T.H., Klein, A.M., Regetz, J., Ricketts, T.H., 2007. Pollination and other ecosystem services produced by mobile organisms: a conceptual framework for the effects of land-use change. Ecol. Lett. 10, 299–314.
Kuniuki, S., 2001. Effects of organic fertilization and pesticide application on growth and yield of field-grown rice for 10 years. Jpn. J. Crop Sci. 70 (4), 530–540.
Lawford, R., Bogardi, J., Marx, S., Jain, S., Wostl, C.P., Knüppe, K., Ringler, C., Lansigan, F., Meza, F., 2013. Basin perspectives on the water–energy–food security nexus. Curr. Opin. Environ. Sustain. 5 (6), 607–616.
Lee, Sally, 1991. Pesticides. Franklin Watts, Yew York.
Markantonis, V., Reynaud, A., Karabulut, A.A., El Hajj, R., Altinbilek, D., Awad, I.M., Brugemann, A., Constantianos, V., Mysiak, J., Lamaddalena, N., Matoussi, M.S., Montero, H., Pistocchi, A., Pretato, U., Tahboub, N., Tunçok, I.K., Ünver, O., Van Ek, R., Willaarts, B., Sönmez, B., Turan, Z., Bidoglio, G., 2015. Policy Note: Water-Energy-Food Nexus Promoting Growth in the Mediterranean: the Current Status and the Way Forward. Water Economics and Policy, Special issue on Water Nexus and Economic Growth in the Mediterranean Region (in progress).
MEA (Millennium Ecosystem Assessment), 2005. Ecosystems and Human Well-being: Synthesis. World Resources Institute, Washington, DC.
Mekonnen, M.M., Gerbens-Leenes, P.W., Hoekstra, A.Y., 2016. Future electricity: the challenge of reducing both carbon and water footprint. Sci. Total Environ.
Miller, G.T., 2004. Sustaining the Earth, sixth ed. Thompson Learning, Inc, Pacific Grove, California, pp. 211–216 (Chapter 9).
Mohtar, R.H., 2016. Integrated water, energy, and food governance: a qatari perspective. In: Policy-making in a Transformative State. Palgrave Macmillan UK, pp. 295–307.
Mohtar, R.H., Daher, B., 2016. Water-Energy-Food Nexus Framework for Facilitating Multi-stakeholder Dialogue. Water International, pp. 1–7.
Müller, F., de Groot, R., Willemen, L., 2010. Ecosystem services at the landscape scale: the need for integrative approches. Landsc. Online 23, 1–11. http://dx.doi.org/10.3097/LO.201023.
Muxika, I., Borja, A., Bald, J., 2007. Using historical data, expert judgement and multivariate analysis in assessing reference conditions and benthic ecological status, according to the European Water Framework Directive. Mar. Pollut. Bull. 55 (1), 16–29.
Notarnicola, B., Sala, S., Antón, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. J. Clean. Prod. 140 (2), 399–409.
Olsson, G., 2013. Water, energy and food interactions: challenges and opportunities. Front. Environ. Sci. Eng. 7 (5), 787–793. http://dx.doi.org/10.1007/s11783-013-0526-z.

Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43 (11), 4098–4104.
Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., 2010. The impacts of climate change on water resources and agriculture in China. Nature 467 (7311), 43–51.
Potts, S., Biesmeijer, J., Kremen, C., Neumann, P., Schweiger, O., Kunin, W., 2010. Global pollinator declines: trends, impacts and drivers. Trends Ecol. Evol. 25, 345–353.
Qiu, G.Y., Li, W., Li, L., Zhang, Q., Yang, Y., 2014. Water and energy nexus in China: current situation and future perspective in energy industry, water industry and agriculture. J. Fundam. Renew. Energy Appl.
Ramírez, C.A., Worrell, E., 2006. Feeding fossil fuels to the soil: an analysis of energy embedded and technological learning in the fertilizer industry. Resour. Conserv. Recycl. 46 (1), 75–93.
Rasul, G., 2014. Food, water, and energy security in South Asia: a nexus perspective from the Hindu Kush Himalayan region. Environ. Sci. Policy 39, 35–48.
Ringler, C., Bhaduri, A., Lawford, R., 2013. The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Curr. Opin. Environ. Sustain. 5 (6), 617–624.
Rosenzweig, C., Parry, M.L., 1994. Potential impact of climate change on world food supply. Nature 367 (6459), 133–138.
Ruimy, A., Kergoat, L., Bondeau, A., Intercomparison, T., Model, P.O.T.P.N., 1999. Comparing global models of terrestrial net primary productivity (NPP): analysis of differences in light absorption and light-use efficiency. Glob. Chang. Biol. 5, (S1), 56–64.
Sala, S., Farioli, F., Zamagni, A., 2013a. Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: Part 1. Int. J. life Cycle Assess. 18 (9), 1653–1672.
Sala, S., Farioli, F., Zamagni, A., 2013b. Life cycle sustainability assessment in the context of sustainability science progress (part 2). Int. J. Life Cycle Assess. 18 (9), 1686–1697.
Sala, S., Anton, A., McLaren, S., Notarnicola, B., Saouter, E., Sonesson, U., 2017. In quest of reducing the environmental impacts of food production and consumption. J. Clean. Prod. 140 (2), 387–398. http://dx.doi.org/10.1016/j.jclepro.2016.09.054.
Sanders, K.T., Masri, S.F., 2016. The energy-water agriculture nexus: the past, present and future of holistic resource management via remote sensing technologies. J. Clean. Prod. 117, 73–88.
Sandrock, C., Tanadini, M., Tanadini, L.G., Fauser-Misslin, A., Potts, S.G., Neumann, P., 2014. Impact of chronic neonicotinoid exposure on honeybee colony performance and queen supersedure. PLoS One 9, 1.
Scarlett, L., Boyd, J., 2011. Ecosystem Services: Quantification, Policy Applications, and Current Federal Capabilities. Resources for the Future Discussion Paper, pp. 11–13.
Schmidhuber, J., Tubiello, F.N., 2007. Global food security under climate change. Proc. Natl. Acad. Sci. 104 (50), 19703–19708.
Scott, C.A., Pierce, S.A., Pasqualetti, M.J., Jones, A.L., Montz, B.E., Hoover, J.H., 2011. Policy and institutional dimensions of the water–energy nexus. Energy Policy 39 (10), 6622–6630.
SDG (Sustainable Development Goals), 2015. Targets and Topics Related to the Sustainable Development Goals. Available at: https://sustainabledevelopment.un.org/?menu=1300 (Accessed November 2015).
SEI (Stockholm Environment Institute), 2015a. LEAP-long Range Energy Alternatives Planning System Software. SEI's US Center. Available at: http://sei-us.org/EnergyModeling (Accessed December 2015).
SEI (Stockholm Environment Institute), 2015b. WEAP-water Evaluation and Planning System Software. Available at: http://www.weap21.org/index.asp (Accessed December 2015).
Stehfest, E., van Vuuren, D., Bouwman, L., Kram, T., 2014. Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model Description and Policy Applications. Netherlands Environmental Assessment Agency (PBL).
Tallis, H., Polasky, S., 2009. Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. Ann. N. Y. Acad. Sci. 1162, 265–283.
Tallis, H., Ricketts, T., Guerry, A., Wood, S., Sharp, R., 2011. Invest 2.3.0 User's Guide: Integrated Valuation of Environmental Services and Tradeoffs. The Natural Capital Project Stanford.
TEEB (The Economics of Ecosystems and Biodiversity), 2010. The economics of ecosystems and biodiversity: ecological and economic foundations. In: Kumar, Pushpam (Ed.), Earthscan, London and Washington.
Texas A&M AgriLife Research, 2015. Environmental Policy Integrated Climate (EPIC) Model- Agricultural Policy/Environmental EXtender Model (APEX). Available at: http://epicapex.tamu.edu/ (accessed December 2015).
Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., Williams, R., 2009. Beneficial biofuels—the food, energy, and environment trilemma. Science 325 (5938), 270–271.
UN-UNITAR (United Nations Institute for Training and Research), 2016. Introduction to Water Diplomacy, Module I-water Resources: Conflicts and Cooperation. UNESCO-IHP technical documents, Switzerland.
Urea Outlook, 2002. Issue 2002-1. Fertecon Ltd, Kent, UK.
Villa, F., 2009. ARIES (ARtificial Intelligence for Ecosystem Services): a new tool for ecosystem services assessment, planning, and valuation. In: 11th Annual BIOECON Conference on „Economic Instruments to Enhance the Conservation and Sustainable Use of Biodiversity“ Venice, Italy.
Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth science. Science 289 (5477), 284–288.
Wang, S., Chen, B., 2016. Energy–water nexus of urban agglomeration based on multiregional input–output tables and ecological network analysis: a case study of the Beijing–Tianjin–Hebei region. Appl. Energy 178, 773–783.
Ware, G.W., 1983. Pesticides. In: Theory and Application. WH Freeman & Co.
Warrens, M.J., 2010. A formal proof of a paradox associated with Cohen's kappa. J. Classif. 27 (3), 322–332.
World Economic Forum, 2011. Global Risks 2011, sixth ed. World Economic Forum, Cologne/Geneva.
Weitz, N., Nilsson, M., Davis, M., 2014. A nexus approach to the Post-2015 agenda: formulating integrated water, energy, and food SDGs. SAIS Rev. Int. Aff. 34 (2), 37–50.
Wong, K.V., 2015. Energy–water–food nexus and recommendations for security. J. Energy Resour. Technol. 137 (3), 034701.
Wong, K.V., Pecora, C., 2015. Recommendations for energy–water–food nexus problems. J. Energy Resour. Technol. 137 (3), 032002.
WWAP (United Nations World Water Assessment Programme), 2014. The United Nations World Water Development Report 2014: Water and Energy. UNESCO, Paris.
You, F., Tao, L., Graziano, D.J., Snyder, S.W., 2012. Optimal design of sustainable cellulosic biofuel supply chains: multiobjective optimization coupled with life cycle assessment and input–output analysis. AIChE J. 58 (4), 1157–1180.
Zulian, G., Maes, J., Paracchini, M.L., 2013. Linking land cover data and crop yields for mapping and assessment of pollination services in Europe. Land 2 (3), 472–492.